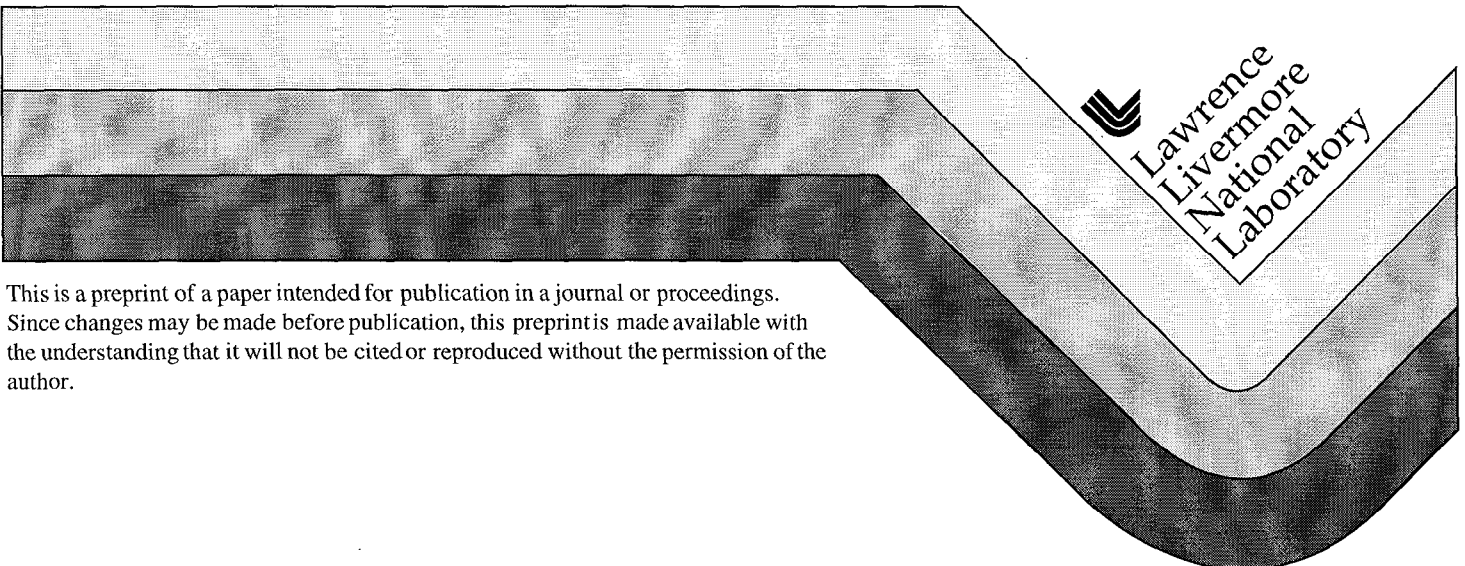


High-Accuracy Calibration of an Adaptive Optics System Using a Phase Shifting Diffraction Interferometer

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High-accuracy calibration of an adaptive optics system using a phase shifting diffraction interferometer

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ABSTRACT

A phase-shifting diffraction interferometer (PSDI) has been integrated into an adaptive optics (AO) system developed by LLNL for use on the three meter Shane telescope at Lick Observatory. The interferometer is an all fiber optic design, which is extremely compact. It is useful for calibrating the control sensors, measuring the aberrations of the entire AO optical train, and measuring the influence functions of the individual actuators on the deformable mirror. The PSDI is particularly well suited for this application because it measures converging, quasi-spherical wavefronts, such as are produced by an AO imaging system. Thus, a PSDI can be used to measure the aberrations of the entire AO system, in-situ and without errors introduced by auxiliary optics. This provides an extremely accurate measurement (~ 5 nm RMS) of the optical properties of the AO system.

Keywords: phase shifting diffraction interferometer, adaptive optics, calibration.

1. INTRODUCTION

Adaptive optics systems have proven useful for improving the imaging quality of ground based telescopes.¹ After quickly measuring the wavefront quality of a point source object, the AO system can transform the quasi-spherical wavefront produced by the telescope into a spherical one, thereby yielding a good image. The level of correction is dependent on two things. First, a reference state must be known. Most commonly, this is the state of the AO system that maps a point source object into a diffraction limited point image. Second, the modes of the AO system must be measured. This allows the proper shape to be applied to the active optic in order to correct to the image given the measured aberration.

Adding an interferometer to the AO system is useful for achieving both goals. First, the interferometer can be used to accurately measure the quality of the AO system alignment in-situ. Thus, static aberrations of the entire imaging system can be characterized while the AO system is mounted on the telescope. Instead of inferring that a system will produce a good image from metrology of individual optical components and assumption of proper alignment, the quality of the static system is measured directly. This is particularly useful if the imaging quality drifts during normal use of the AO system. Major causes of these drifts include changes in the shape of the optical bench while the telescope pointing is varied and thermally induced variations in mirror shapes and component spacings. In addition, thermally induced changes in the component mounting stresses can cause the imaging quality to vary. Because all of these changes are slow in nature, they can be characterized by an interferometer. A second advantage of using an interferometer is that the influence functions of the various active optic modes also can be measured in-situ. This allows for more accurate correction of the image because the influence functions of the actual system are measured directly rather than inferred from measurements of the active optic alone.

A phase-shifting diffraction interferometer² (PSDI) is particularly well suited for this application. This is because a PSDI operates by using diffraction from a point-like aperture to generate a highly spherical diverging wavefront that is compared interferometrically to an aberrated, quasi-spherical converging wavefront. Since an AO system can be considered as a black box that relays an aberrated point source (the telescope focus) to a corrected, diffraction limited point image, the reference wave output by the PSDI can be fed without modification into the input of the AO system. Likewise, the corrected output of the AO system can be fed without modification into the test arm of the PSDI. This provides for an extremely accurate measurement of the optical properties of the AO system. An additional advantage of using a PSDI is that it can be constructed to be very compact, allowing it to more easily fit in the limited space available on the AO bench.

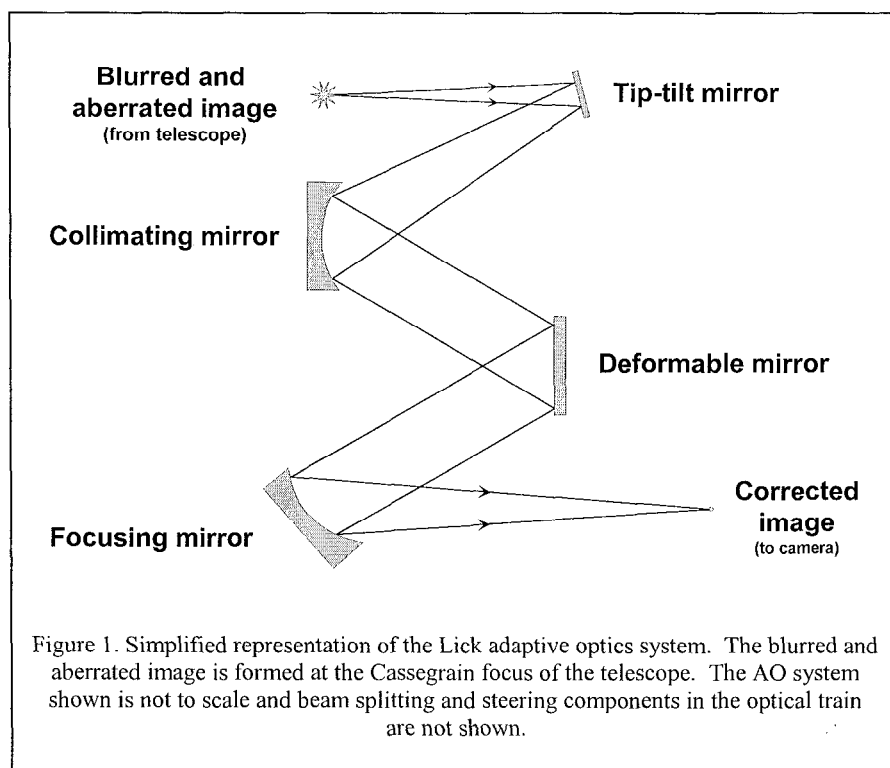
This paper discusses the integration of an all-fiber optic PSDI into the AO system on the Shane telescope at Lick Observatory. The AO system is briefly presented, and a general description of phase measuring interferometers is given. A

detailed description of the compact, fiber optic implementation of a PSDI is included. Results from using the system to measure the AO system are given, along with an analysis of the accuracy of the measurements. Finally, an example of measuring the influence functions of the deformable mirror is given.

2. THE SHANE ADAPTIVE OPTICS SYSTEM

The AO system for the Shane telescope uses a fast moving tip-tilt mirror, which corrects for the blurring due to image movement, and a deformable mirror, which improves the point spread function (Fig. 1). The tip-tilt mirror is placed in the expanding beam after the Cassegrain focus, and the deformable mirror is placed in collimated light between two parabolic mirrors. The first parabola collimates the expanding wave from the input point image, and the second parabola focuses the corrected planar wavefront to a corrected point image. This image is then re-imaged by a scientific camera operating in the infrared. There are also six auxiliary optics in the optical system. Two are dichroic mirrors, used for splitting off light for the sensors that control the tip-tilt and deformable mirrors, and four are beam steering mirrors.

All total, the image created by the AO system passes through or reflects off of 11 optical elements. For this reason, it is preferable to measure the entire AO system rather than measure each component individually and rely on proper alignment procedure to predict the static system performance.

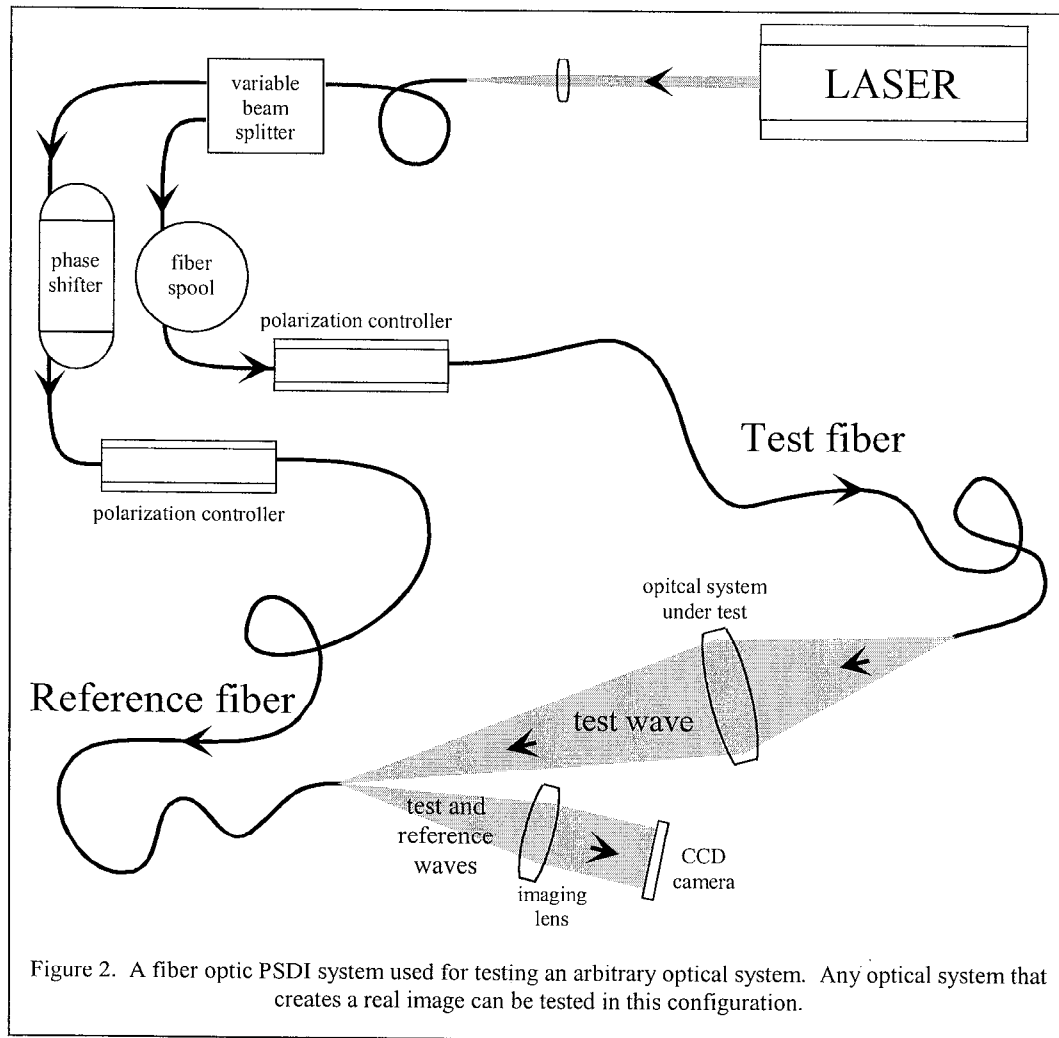


3. PSDI PRINCIPALS OF OPERATION

The PSDI is a relatively new type of interferometer invented in 1996³ for making high accuracy measurements (~ 0.5 nm RMS) of aspheric optics⁴. It retains the advantage of phase shifting interferometers to evaluate a wavefront at a large number of points using well-developed and robust algorithms⁵, but it contains a fundamental improvement. Rather than using a high quality optical surface to generate the reference wave, it uses point-source diffraction instead. This yields a much higher quality reference wave, which dramatically increases the accuracy of the interferometer. For comparison, a standard commercially available Fizeau interferometer (i.e. Zygo GPI or Wyko 6000) offers an accuracy of about 6 to 30 nm RMS, while a PSDI offers an accuracy of less than 0.5 nm RMS in a much smaller package.

The point source that creates the high quality spherical wavefront can be formed two ways. One way is to focus a laser beam onto a pinhole having a diameter on the order of the wavelength. If the pinhole is circularity is good, then it will diffract a highly spherical wavefront. A more flexible way to generate a spherical wave is to focus a laser into a single mode optical fiber. If the fiber is then terminated abruptly in a plane normal to the guiding direction, the light diffracting from the circular core will form a spherical wave. For the Lick AO system, the spherical waves were generated using optical fibers.

As implemented on the LLNL AO system, the PSDI functions similar to a Twyman-Green interferometer⁶. A coherent source is divided into two beams – the reference and test beams. The reference beam is phase shifted in a controlled manner, while the test beam is passed through the AO system (Fig. 2). The two beams are combined in a manner unique to PSDIs. The test beam is focused down onto the end of the reference beam fiber. The fiber end is partially mirrored, which allows the

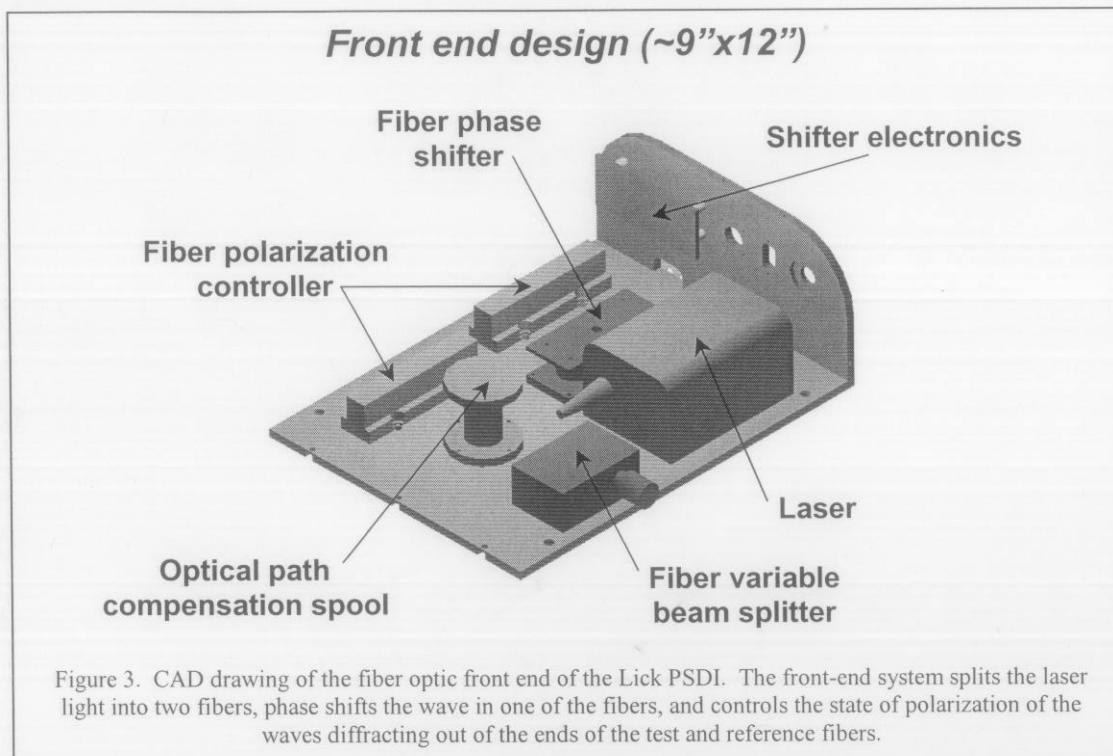


test beam to reflect from the fiber end and combine with the reference wave. By slightly tilting the fiber end relative to the optical axis of the system under test, the reflected test wave does not overlap with the incident test wave.

4. DESIGN OF THE ALL-FIBER PSDI SYSTEM

A difficulty in integrating a PSDI into the Lick AO system is that limited space is available for adding hardware. In order make a system with a much smaller footprint, an entirely fiber optic system was developed. Previous systems for other applications had used discrete optical components and required an area of size 36" x 36". The all fiber optic system occupies a footprint of 9" x 12", approximately 1/12th the size of the discrete systems. The vertical dimension also has been reduced,

from 12" to 8". A CAD drawing of the system is shown below in Figure 3. All of the components in the front-end system are commercially available.

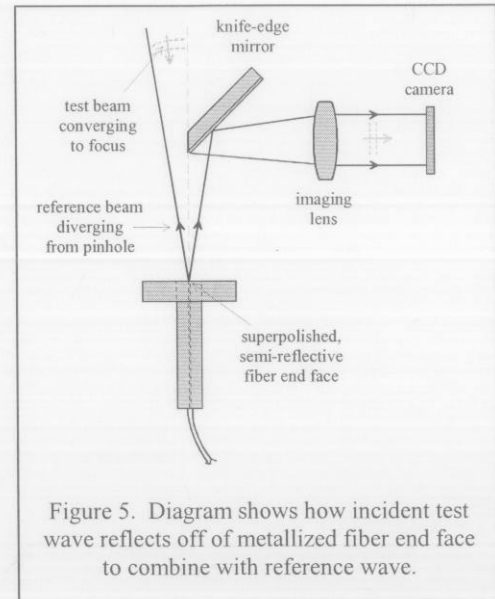
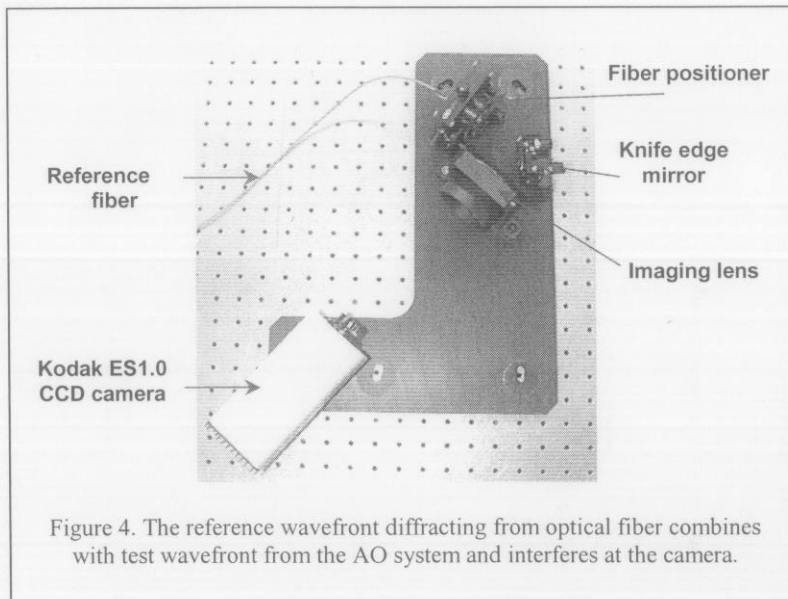


The original all-fiber PSDI used a HeNe laser source, but the low power of the laser (~10mW) required the physical removal of a dichroic beam splitter from the AO system. The HeNe has since been replaced with a compact, low noise double Nd:YAG laser with an optical power of 50 mW and a coherence length greater than ten meters (CrystaLaser, model GCL-050-S). This laser has sufficient power to allow the dichroic to remain in place. The laser light is separated into two fibers by a variable beam splitter (Canadian Instrumentation and Research, model 905) that is used to balance the beam powers at the CCD camera in order to achieve maximum fringe contrast. One fiber goes to the phase shifter in the reference wave arm of the interferometer, and the other fiber goes to a fiber spool that is used to equalize the optical path lengths between the reference and test arms. From there, the fibers each go to polarization controllers (General Photonics, model PolaRITE PLC-02/5). The polarization controllers (PLC) are set so that the polarizations of the test and reference waves are identical at the camera (Kodak, model ES1.0). Upon leaving the PLCs, the fibers run to opposite ends of the AO system. The test fiber runs to the input point of the AO system, and the reference fiber runs to the output point of the AO system. To use the PSDI, the test fiber is inserted into the system using a translation stage so that the end face of the fiber is located at the focus of the telescope. When the PSDI is not in use, the test fiber is translated out of the way to pass the telescope image.

The phase shifter is a commercially available device that consists of 25 windings of fiber around an oval spool (Canadian Instrumentation and Research, model 915). The spool has piezoelectric (PZT) plates along the two long sides. The fiber is epoxied to the PZT plates so that when a voltage is applied to the plates, the fiber is stretched as the plates grow in length. A 10-bit digital-to-analog converter card (National Instruments, model PCI-MIO-16XE-10) inside a Pentium II computer running Windows NT generates the linear ramp signal sent to the phase shifter. The image is digitized at 30 fps using a PCI frame grabber (Imaging Technology, model IM-PCI w/AM-DIG).

Once the test wave passes through the AO system, it converges down onto the end of the reference fiber. It then reflects off of the reference fiber to combine with the diverging reference wavefront diffracting out of the end of the fiber. The end face of the reference optical fiber is super polished (RMS roughness < 1Å) to assure that the shape of the fiber end face does not distort the reflected light. A knife-edge mirror then steers the two beams through an imaging lens and onto a CCD camera. The knife-edge mirror passes half of the cone of light diffracting from the reference fiber, and reflects half towards the camera. Since the numerical aperture of the beam exiting the AO system is very small ($f_{\#} \approx 27$), it is not clipped by the knife-

edge as it focuses down onto the reference fiber. This optical system that allows for the interference of the beams test and reference waves is shown in the photograph below (Fig. 4). A diagram of the system is shown in Figure 5.



5. ACCURACY OF THE INITIAL SYSTEM TEST

The PSDI was mounted on the AO system breadboard and initial repeatability tests were performed. The tests were performed in the observatory dome, but before the system was mounted on the telescope. It was expected that air currents in the 5.8 meter optical path and vibrations of the 8 reflective optics would lead to noise in the measurement. However, as such noise is typically random, it is possible to make multiple measurements and average them to reduce the noise. A set of 25 measurements was taken one at a time and averaged together to form a baseline measurement. Then each measurement was individually compared to the baseline. The typical difference between a single measurement and the baseline was 18.6 nm RMS, with a standard deviation of 9.1 nm RMS. Averaging groups of four measurements, and comparing them to the baseline yielded an error of 9.7 nm RMS, with a standard deviation of 3.9 nm RMS. As expected for N measurements of a system with random noise, the RMS error dropped as $1/\sqrt{N}$. As groups of nine and 16 were compared to the total set, the noise dropped more quickly. This is because these groupings no longer appear like independent measurements when compared to a baseline formed with only 25 measurements. The various groupings are tabulated below (Table 1).

No. of averages	Average RMS error (nm)	Standard deviation
1	18.6	9.08
4	9.66	3.91
9	5.23	-
16	3.58	-

Table 1. Average RMS error of a set of averaged measurements tabulated by the number of measurements in the set.

A histogram for the single measurement results is shown below in Figure 6. Each bin in the histogram is 5 nm wide. The minimum difference was 7.8 nm RMS, and the maximum was 48 nm RMS. As can be seen, it is reasonable to treat the noise as random, and nine or more averages should yield a measurement with a RMS error of less than 10 nm. To achieve an accuracy of better than $1/100^{\text{th}}$ of a wave in the visible, approximately 16 averages would be required. At a processing time of 8 seconds per average on a 300MHz Pentium II, it takes approximately 2 minutes to make a measurement accurate to better than $1/100^{\text{th}}$ of a wave.

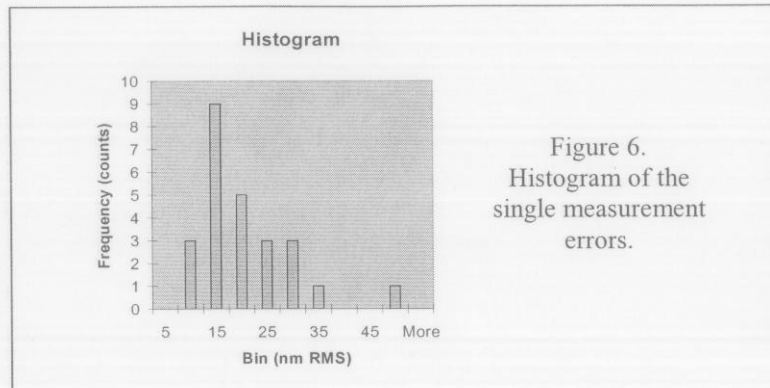


Figure 6.
Histogram of the
single measurement
errors.

6. WAVEFRONT MEASUREMENT AT THE DEFORMABLE MIRROR

In all of the measurements, the imaging lens was focused on the deformable mirror, which forms the pupil of the AO system. This forms a baseline reference measurement of the system in its static state. This along with the influence functions of the individual actuators allows the optimal deformations of the mirror needed to improve the wavefront can be calculated. A measurement of the wavefront at the deformable mirror in its "off" state is shown below in Figure 7. A drawing of the deformable mirror showing its actuator array is given in Figure 8 (Note that due to the beam steering in the AO system, the image in Figure 7 is rotated relative to the drawing in Figure 8). The peak-to-valley deviation of the wavefront is $1.65\ \mu\text{m}$, and the RMS deviation is 133 nm. This wavefront is flat to within $1/6^{\text{th}}$ of the 632.8 nm measurement wavelength, which corresponds to a Strehl ratio of 0.36. The accuracy of this measurement is approximately 5 nm RMS. When the wavefront has been freshly flattened using the phase diversity method, Strehl ratios of 0.45 have been obtained. It is expected that the PSDI can be used to flatten the wavefront to obtain Strehl ratios better than 0.8 once the system is fully automated. It should be noted that improving the Strehl ratio from 0.36 to 0.8 at 632.8 nm, only improves the Strehl ratio at $2.2\ \mu\text{m}$ from 0.92 to 0.98. The real advantage in using the PSDI to calibrate the system is that it takes much less time than the current method (image sharpening using phase-diversity)⁷ and is more robust in the presence of large phase errors. Eventually, calibration to the nanometer level will be useful in planet detection⁸ with ground based telescopes. For space based telescopes, calibration to the sub-nanometer level is desirable.

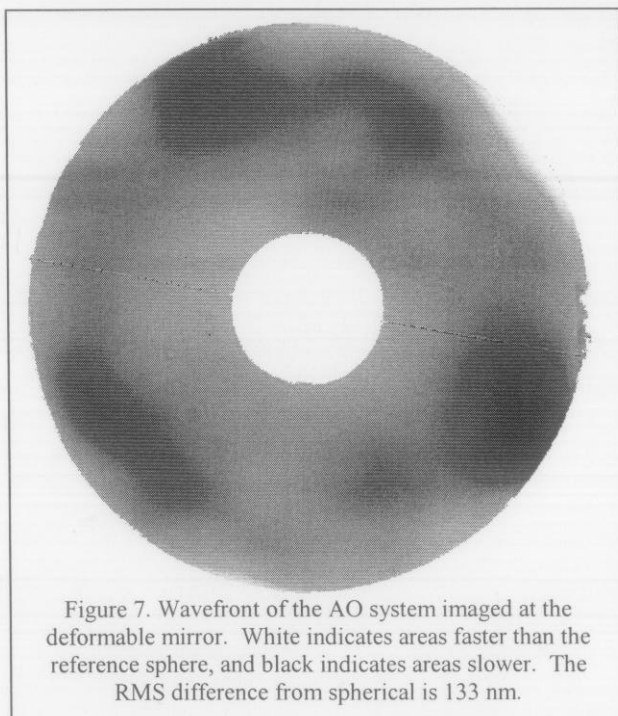


Figure 7. Wavefront of the AO system imaged at the deformable mirror. White indicates areas faster than the reference sphere, and black indicates areas slower. The RMS difference from spherical is 133 nm.

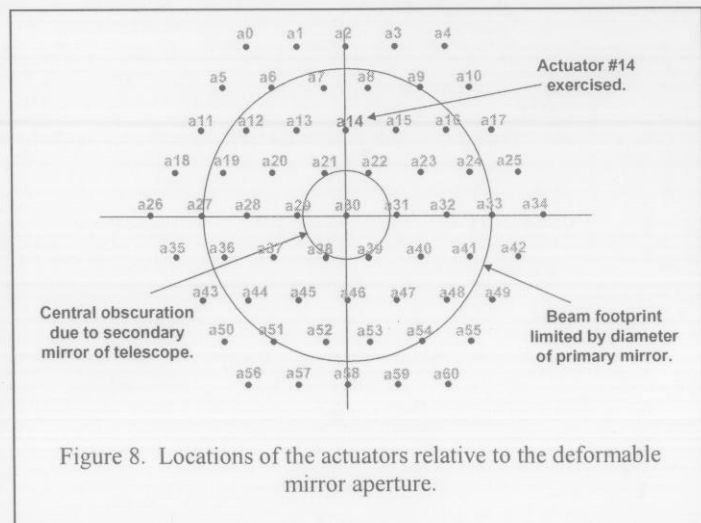
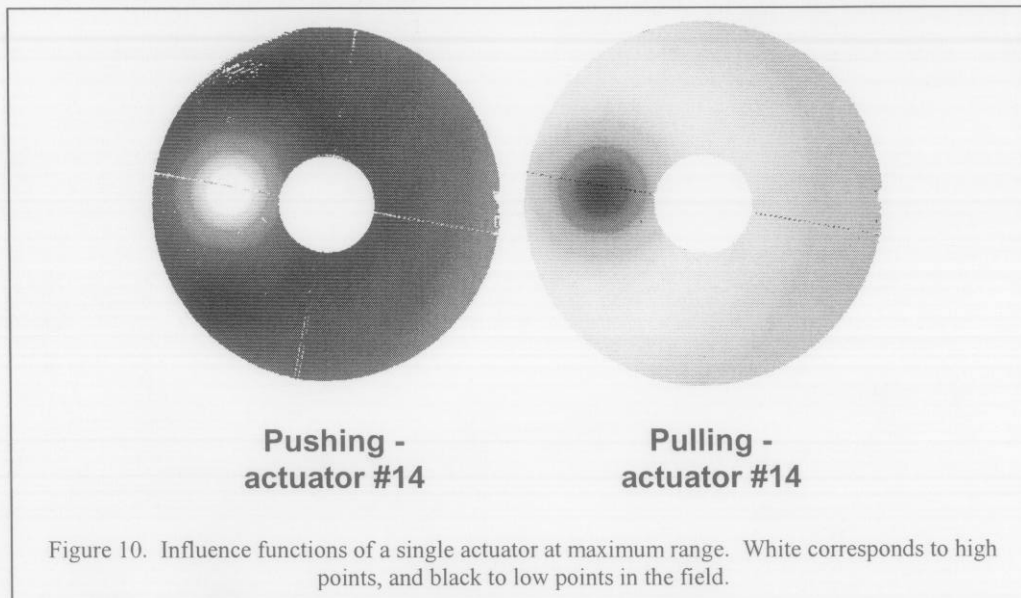
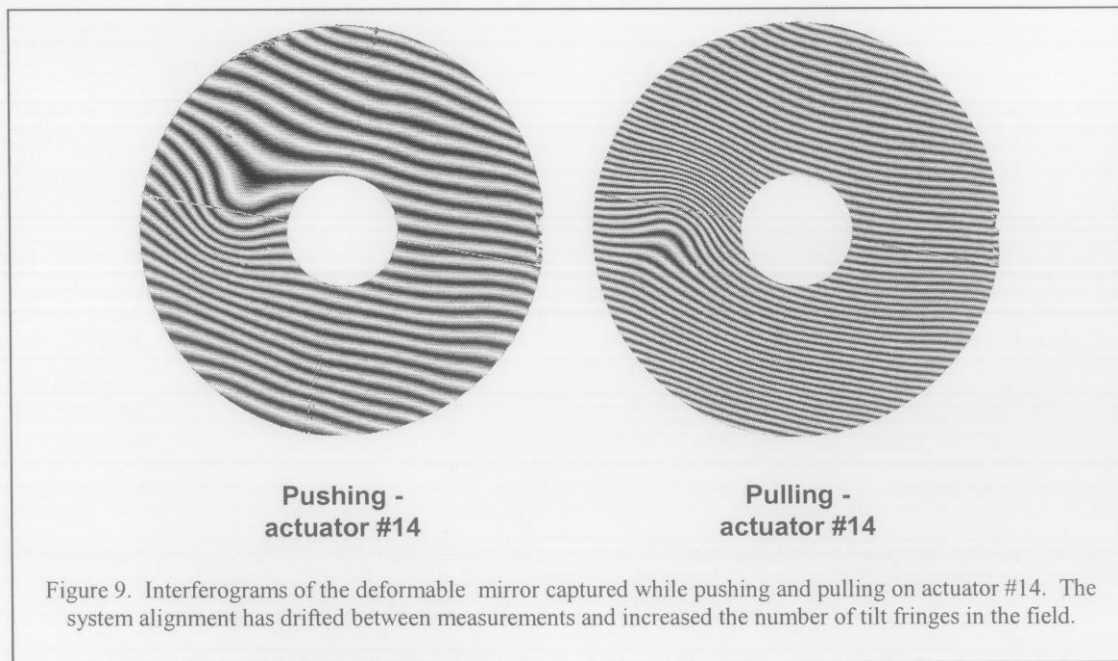
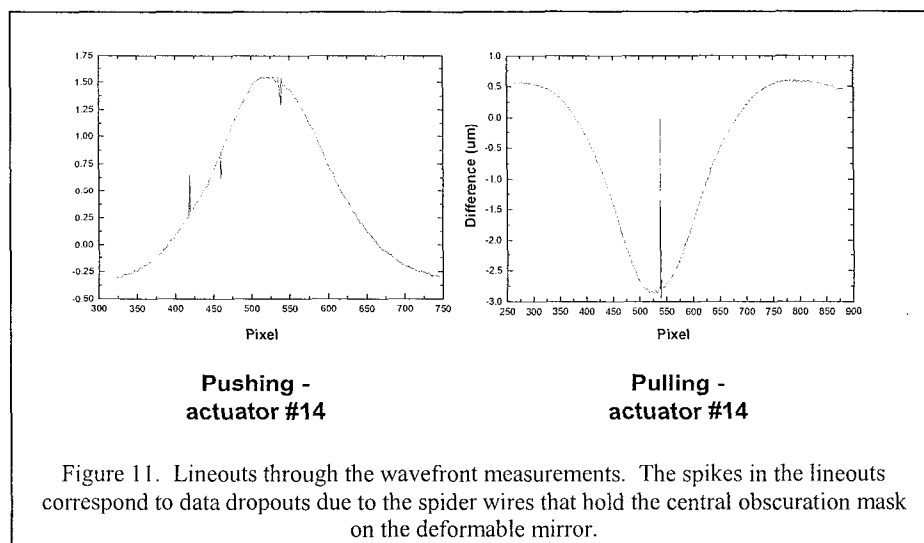


Figure 8. Locations of the actuators relative to the deformable mirror aperture.

7. INFLUENCE FUNCTION OF A SINGLE ACTUATOR

A measurement of the AO system can also be made when a single actuator is either pushed or pulled. The baseline measurement of the inactive system can then be subtracted from this measurement, and the difference yields the influence function for the particular actuator. Below in Figure 9 are the interferograms corresponding to two measurements of the influence function of mirror actuator #14 as it is pushed and pulled. Note that ~30-60 tilt fringes have been introduced to overcome a problem with multiple pass noise. As can be seen in wavefront measurements (Fig. 10), there is a slight hexagonal shape to the deflection because of the hexagonal layout of the actuators. However, the influence function of the actuator is roughly Gaussian in nature. Lineouts through the center of the deflection area better display the magnitude of the wavefront change and are shown below in Figure 11. Note that the wavefront deformation is not equal to the actual mirror deformation because of the reflection, and there is also an obliquity factor due to the light not being normally incident. An image of the fringes in the pushing and pulling modes is shown below.





One should note that having the ability to measure the influence functions does not necessarily mean that an interferometer can be used for closed-loop control. Generally, the data acquisition time is too long. Rather, the interferometer can be used to accurately generate the control matrix that is used by a faster, less accurate control system.

8. CONCLUSION

It has been demonstrated that a phase-shifting diffraction interferometer can be conveniently added to an adaptive optics system. For reasonable acquisition times, the PSDI measurement has an accuracy of approximately 5 nm RMS, limited primarily by vibrations and air turbulence. By averaging for a longer time, the measurement can be driven down to ~0.5 nm RMS, the absolute accuracy of the interferometer. The interferometer is useful for measuring overall system alignment and can act as a reference for re-establishing system alignment when drifts have occurred. The PSDI can also measure the influence functions of the individual actuators so that more accurate corrections can be made.

9. ACKNOWLEDGEMENTS

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